Laboratory demonstrations of high-contrast coronagraphic imaging

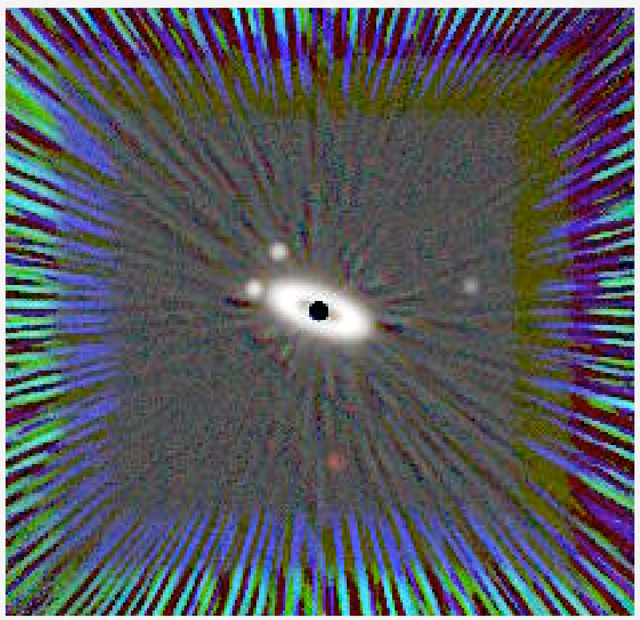
J. Trauger, B. Gordon, B. Kern, A. Kuhnert
D. Moody, A. Niessner, F. Shi
Jet Propulsion Laboratory
California Institute of Technology

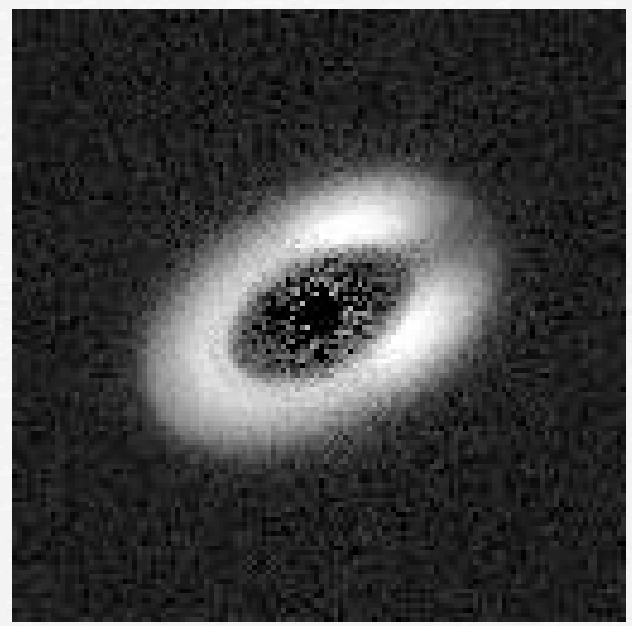
Earth Science Technology Conference
University of Maryland -- 27 June 2006

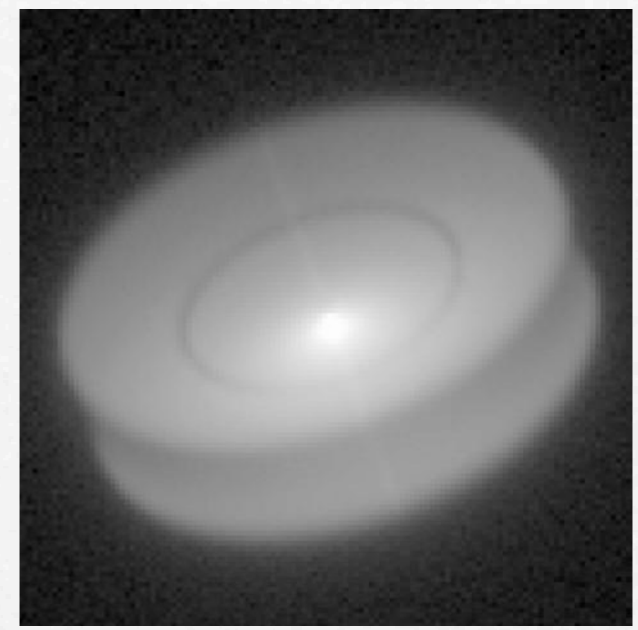
Abstract -- Coronagraphic imaging technology

- Actively corrected space coronagraphy is a technology pathway towards the direct imaging and spectroscopy of nearby exo-solar planetary systems, including the Terrestrial Planet Finder.
- Extremely high contrast is required at visible wavelengths: a mature Jovian planet at 5 AU is approximately one *billion* times fainter than the central star.
- Terrestrial planets at 1 AU are approximately *10 billion* times fainter than the stars they orbit.
- Precision wavefront correction (hardware and nulling algorithms) and a number of basic coronagraph configurations have been demonstrated in JPL's High Contrast Imaging Testbed (HCIT).
- Demonstrated contrast exceeds billion-to-one at the fourth Airy ring ($4\lambda/D$) in narrowband light.
- Ongoing work includes spectrally broad illumination (10-20% bandwidth) and alternative coronagraph configurations.

Coronagraphic imaging science

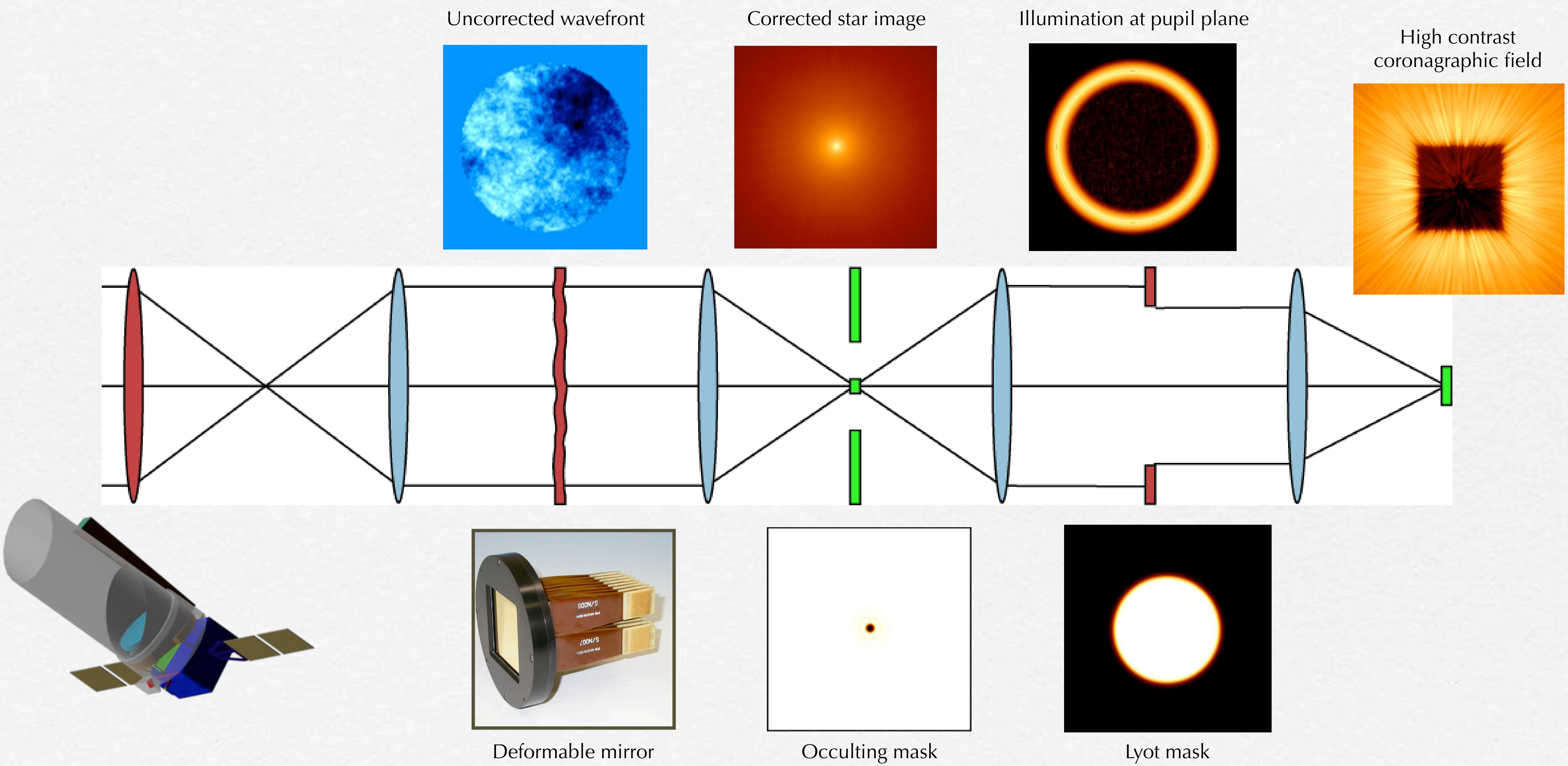




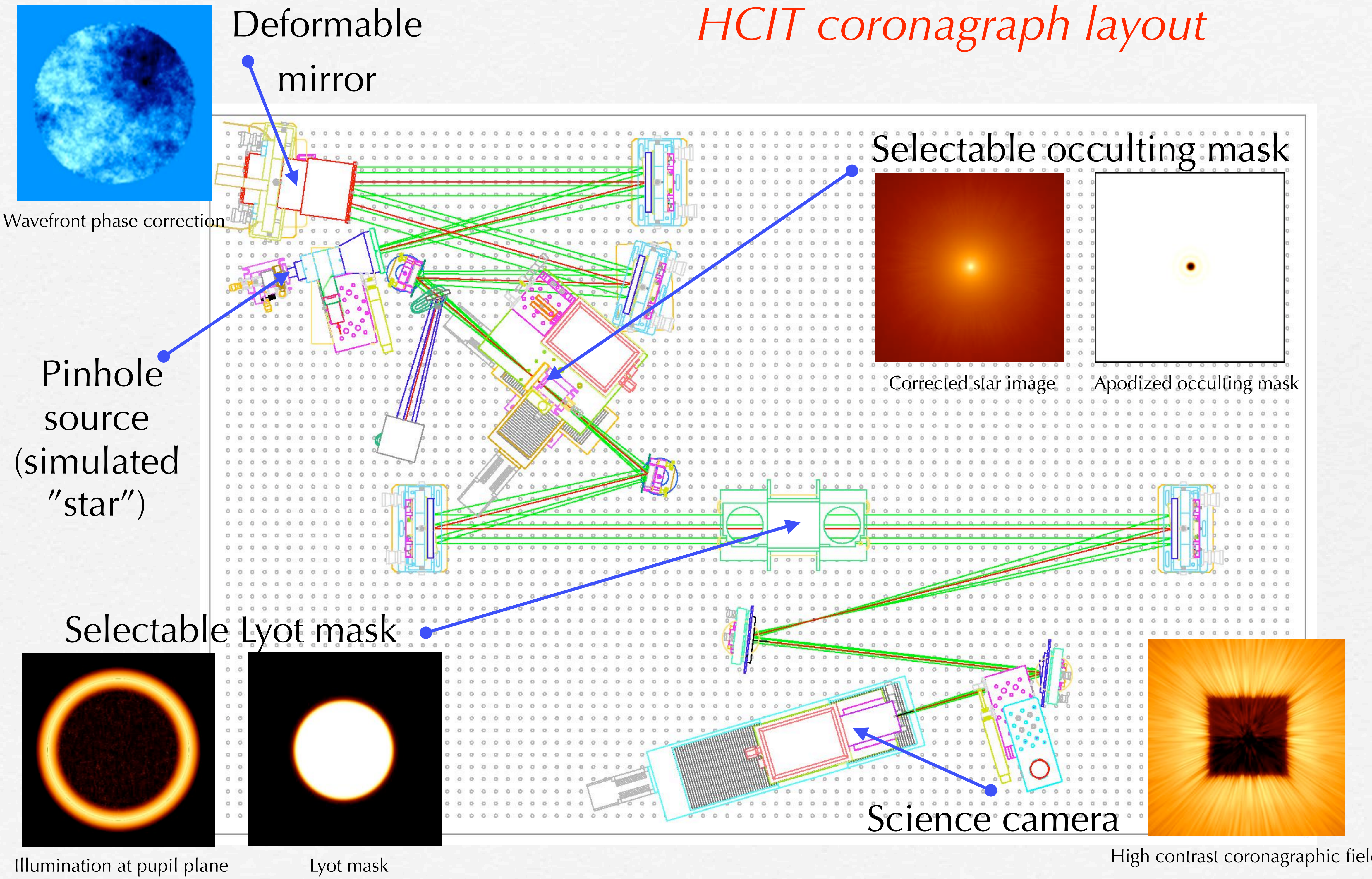


Direct coronagraphic imaging from space will provide access to planets in context with their host planetary systems (at left), planet-induced structures in debris disks (center), and the early formation of planets orbiting young stellar objects (at right).

The High Contrast Imaging Testbed (HCIT) captures the essential elements of a space coronagraph



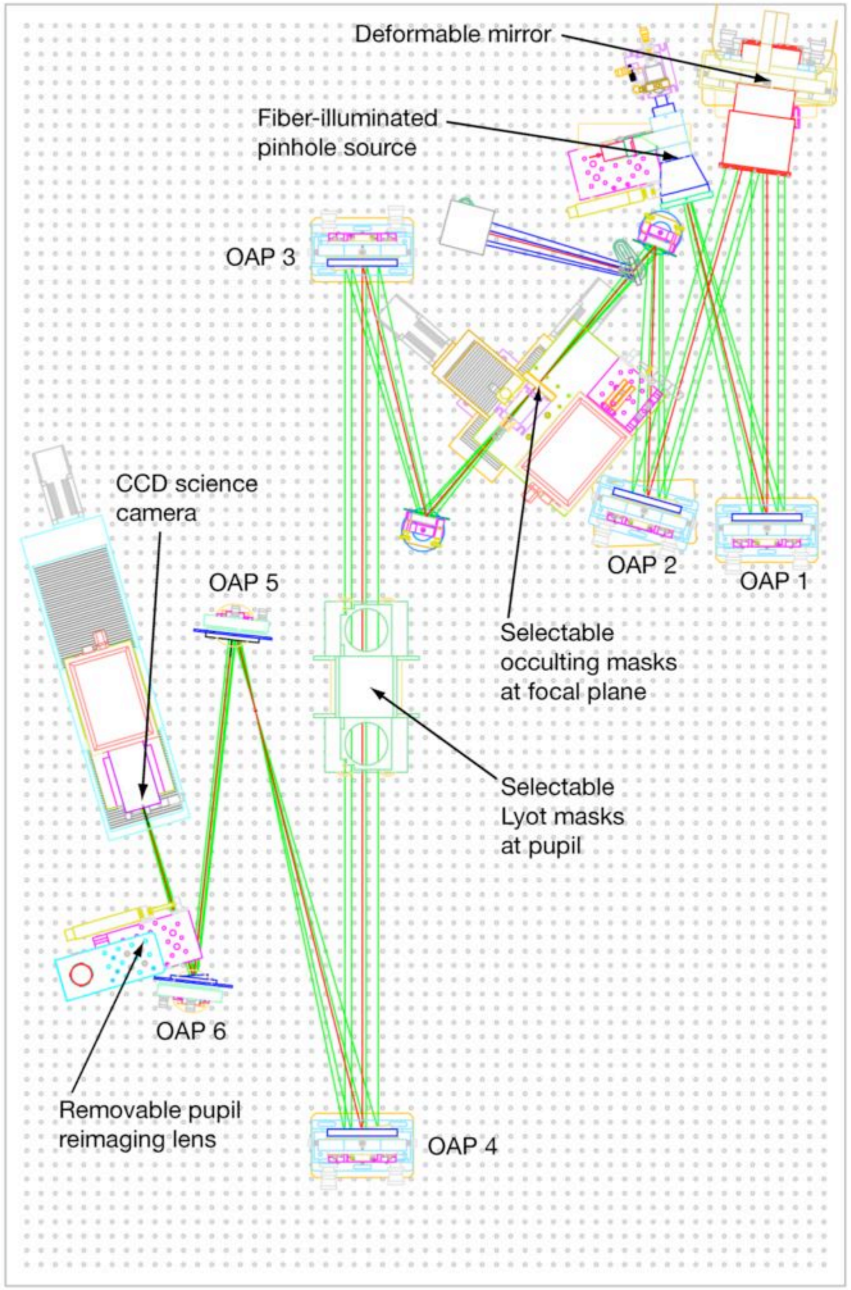
HCIT coronagraph layout

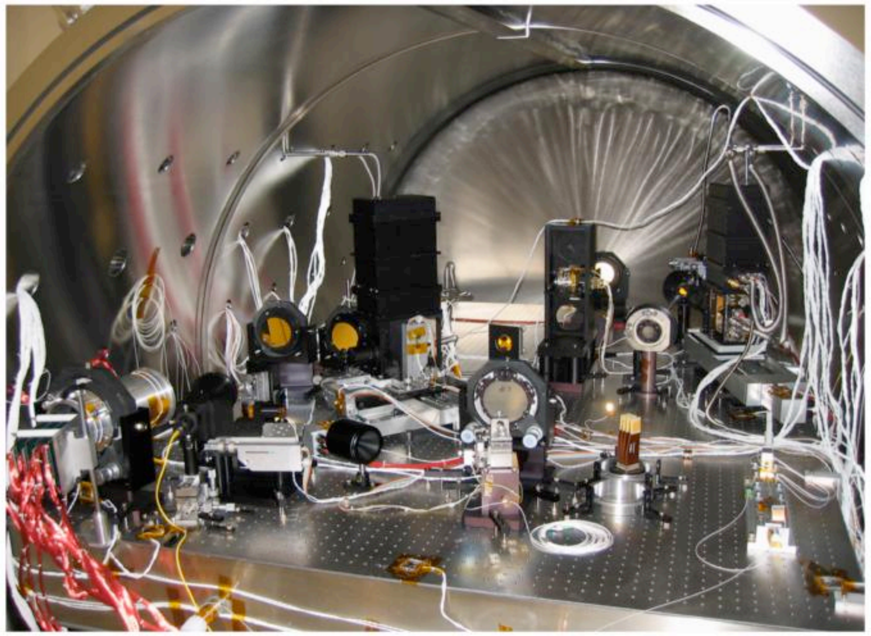


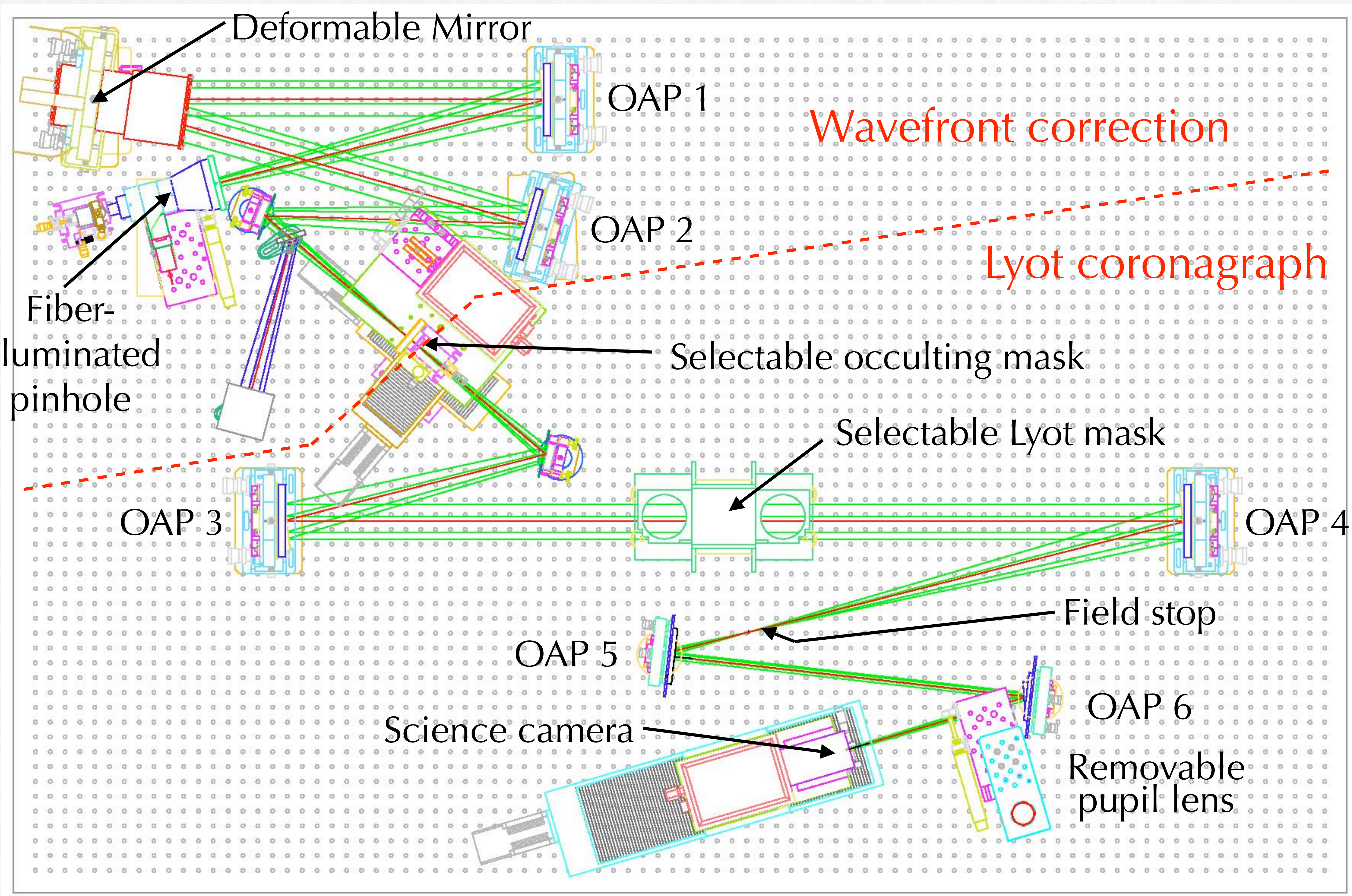
Overview: Laboratory demonstrations of high contrast coronagraphic imaging

- Essential components and optical layout of the HCIT
- Laboratory demonstrations with the Lyot coronagraph
- Alternative coronagraph experiments ongoing on the HCIT
- Summary: recent achievements, future directions

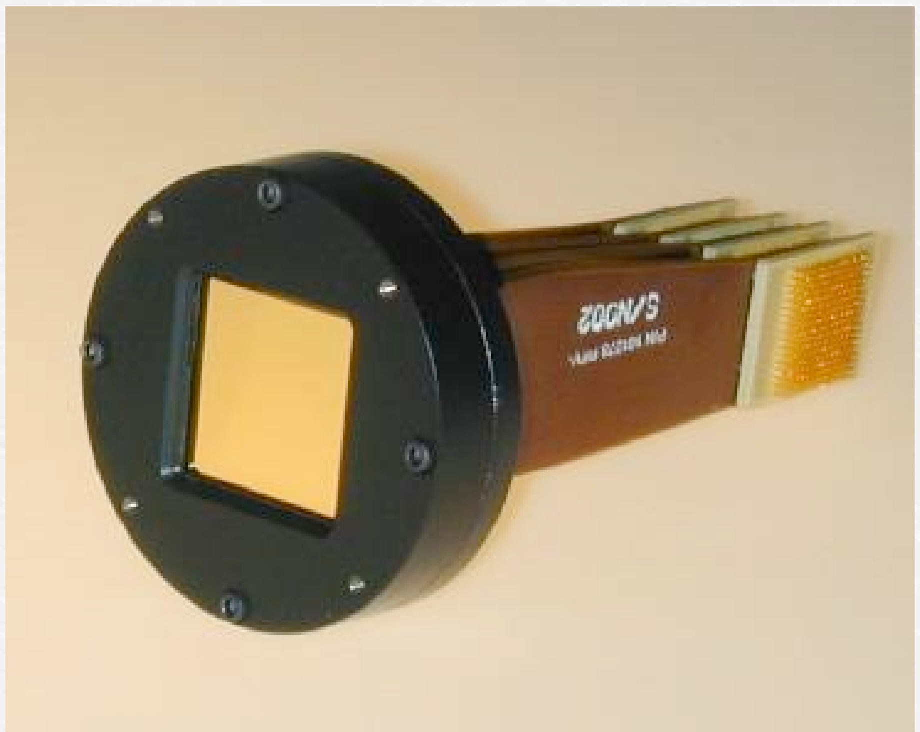
The High Contrast Imaging testbed (HCIT) at JPL






Deformable Mirror
OAP 1
Wavefront correction
OAP 2
Lyot coronagraph
Fiber-illuminated pinhole
Selectable occulting mask
Selectable Lyot mask
OAP 3
OAP 4
Field stop
OAP 5
OAP 6
Science camera
Removable pupil lens

Active wavefront correction with a Deformable Mirror (DM)

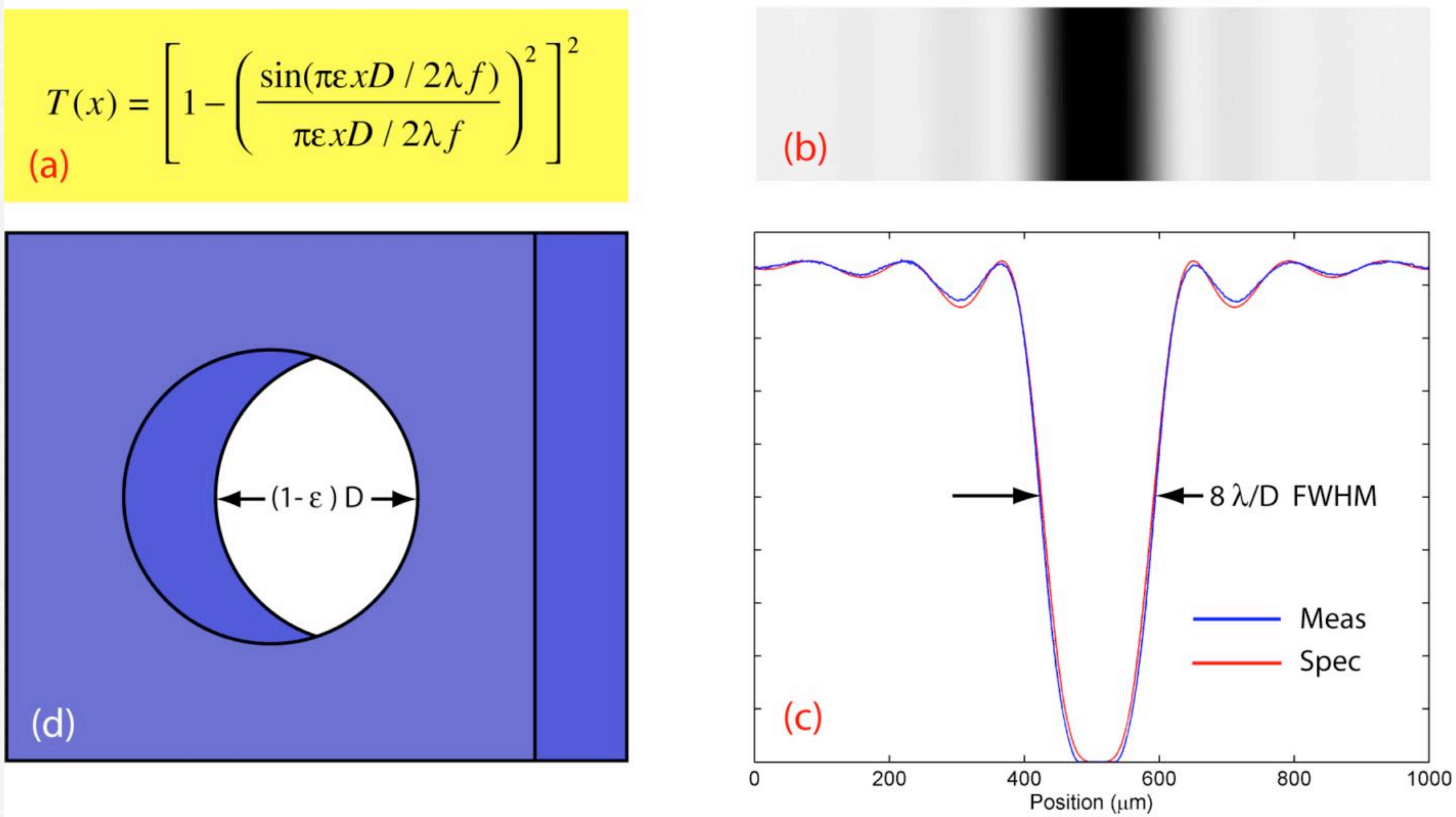


Fifth in a series of Gen2 32x32 mm DMs delivered to JPL by Xinetics. DM surface is polished to $\lambda/100$ rms. Active figure control is better than 0.01 nm rms.

Gen2 64x64 mm DM delivered to JPL. The same 32x32 actuator technology is repeated four times, bonded together, with a single facesheet.

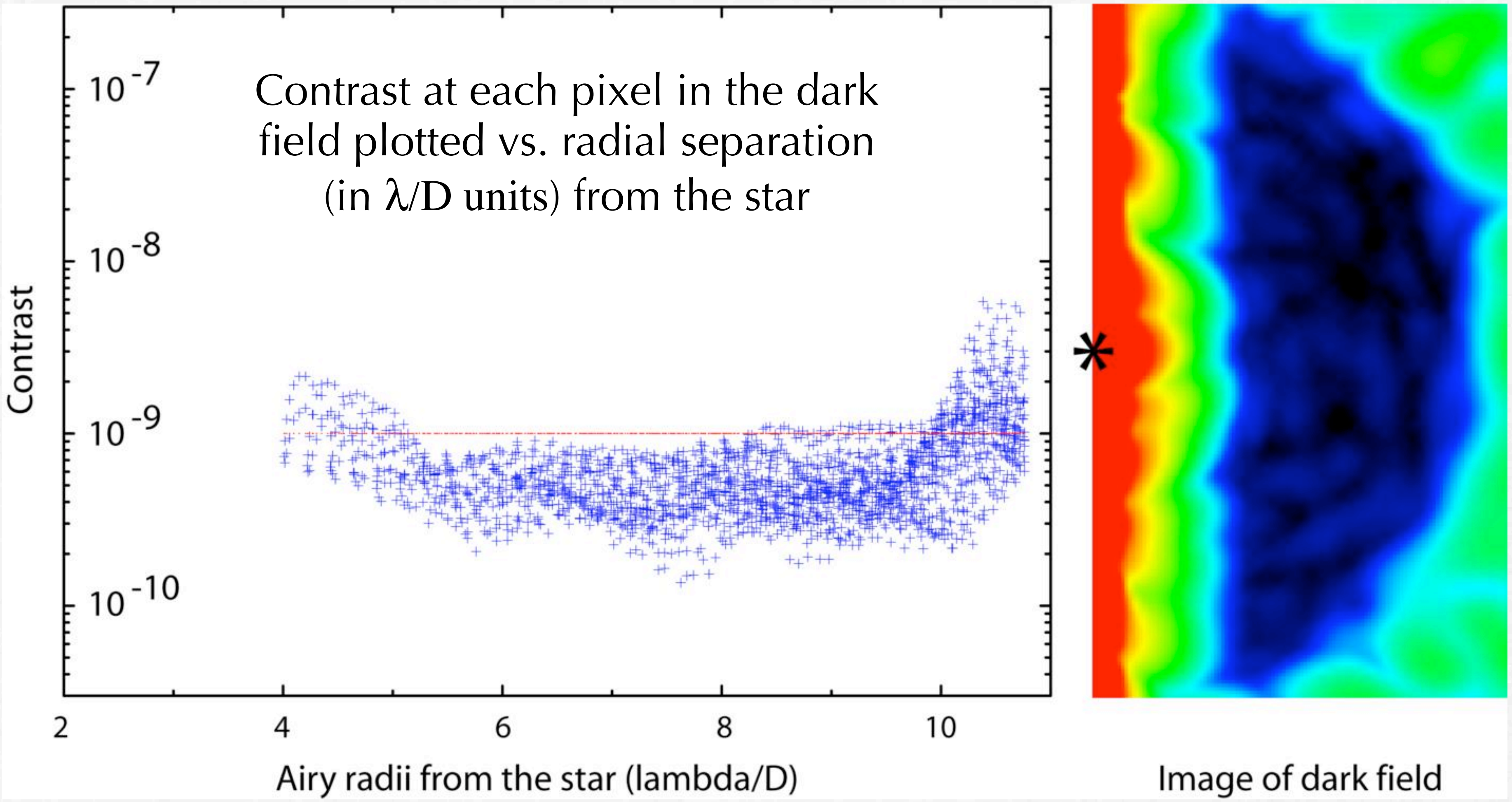
Apodizing elements of the band-limited Lyot coronagraph

$$T(x) = \left[1 - \left(\frac{\sin(\pi \varepsilon x D / 2\lambda f)}{\pi \varepsilon x D / 2\lambda f} \right)^2 \right]^2$$



The Lyot coronagraph consists of a band-limited occulting mask in the highly-corrected focal plane, and a Lyot mask in the following pupil plane. The occulting mask transmittance profile specified in (a) is also shown as a direct microscope image (b) and a measured transmittance profile (c). As shown, the Lyot mask is fashioned from a pair of offset circular apertures (d).

Typical HCIT coronagraph image

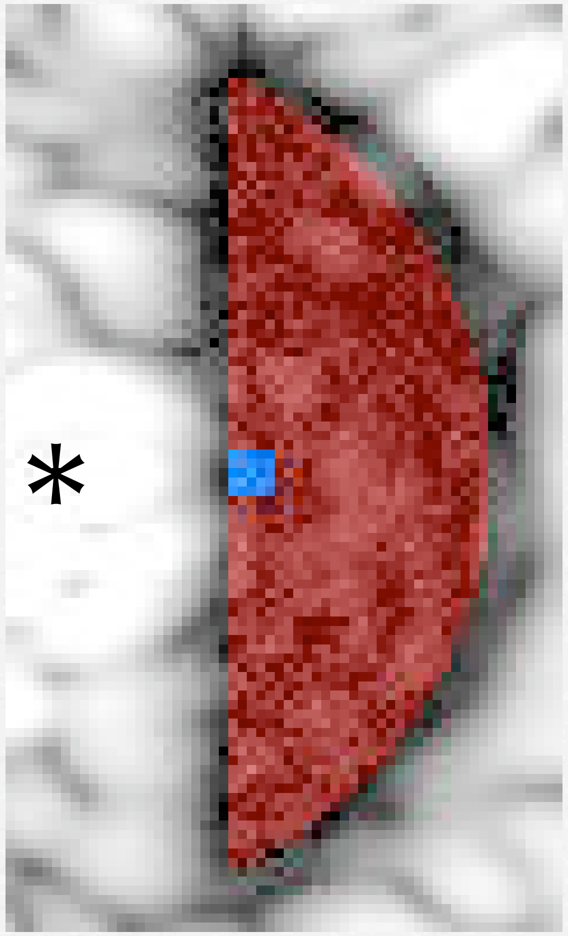


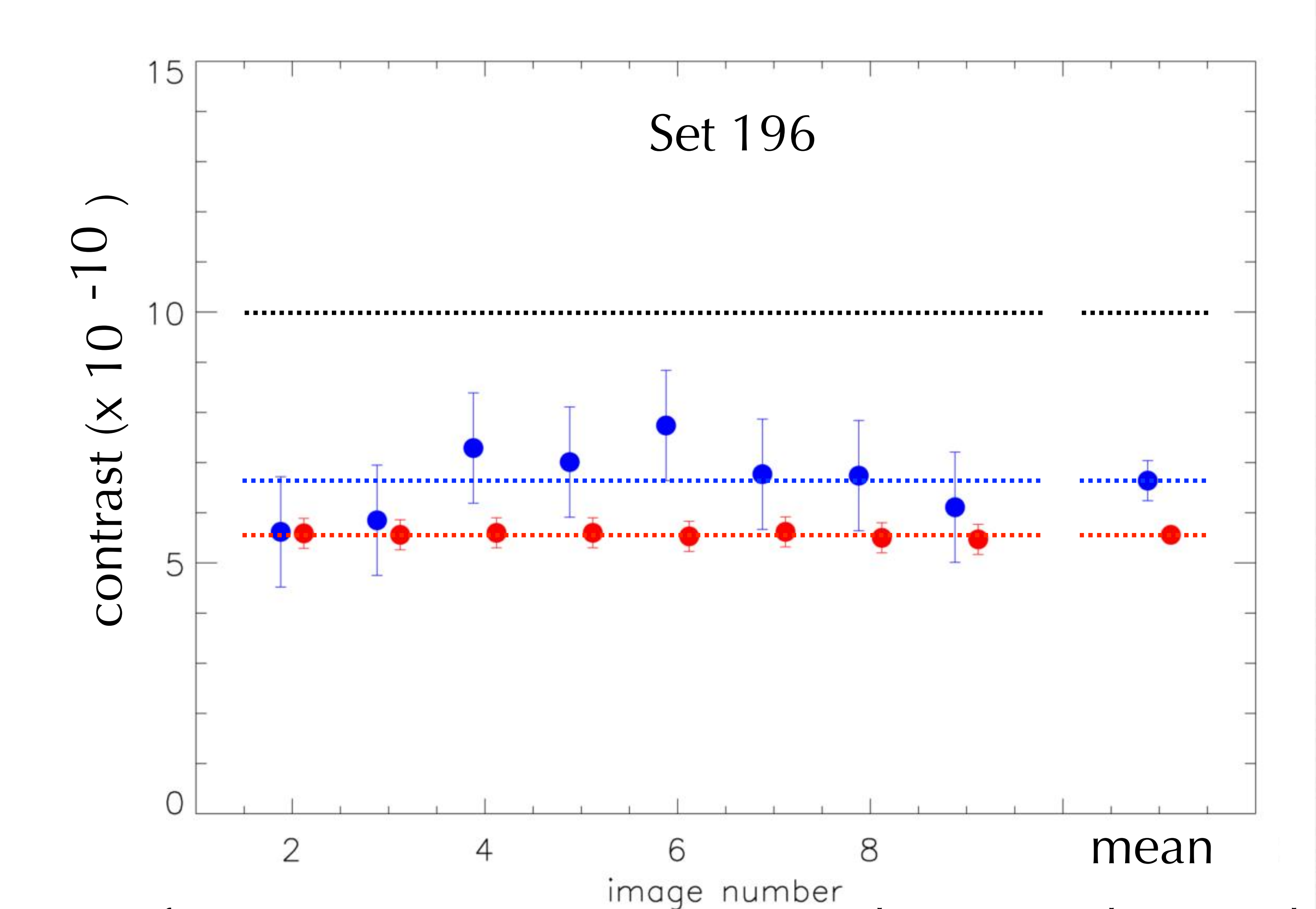
A typical coronagraph dark-field image displayed as pixel-by-pixel contrast data (at left) and color-coded image (at right). Wavefront correction with a single deformable mirror provides a high-contrast "dark field" over half the correctable area. Average contrast is better than billion-to-one in the dark field.

HCIT has repeatably performed the following contrast demonstration:

- Wavefront correction and high contrast imaging in narrowband 785nm light, using the science camera as the sole imaging sensor.
- Average contrast is better than 1 x 10-9 between 4 and 10 λ/D, demonstrates a useful search space for planets.
- Average contrast is better than 1 x 10-9 between 4 and 5 λ/D, demonstrating contrast at the inner working angle.
- Contrast is maintained for one hour or more, while the optical wavefront is actively corrected, demonstrating robustness of the wavefront sensing and control procedure.
- This demonstration is repeated multiple times, starting from a "scratch" setting on the deformable mirror, over a period of one week.

Recent contrast demonstrations with the HCIT

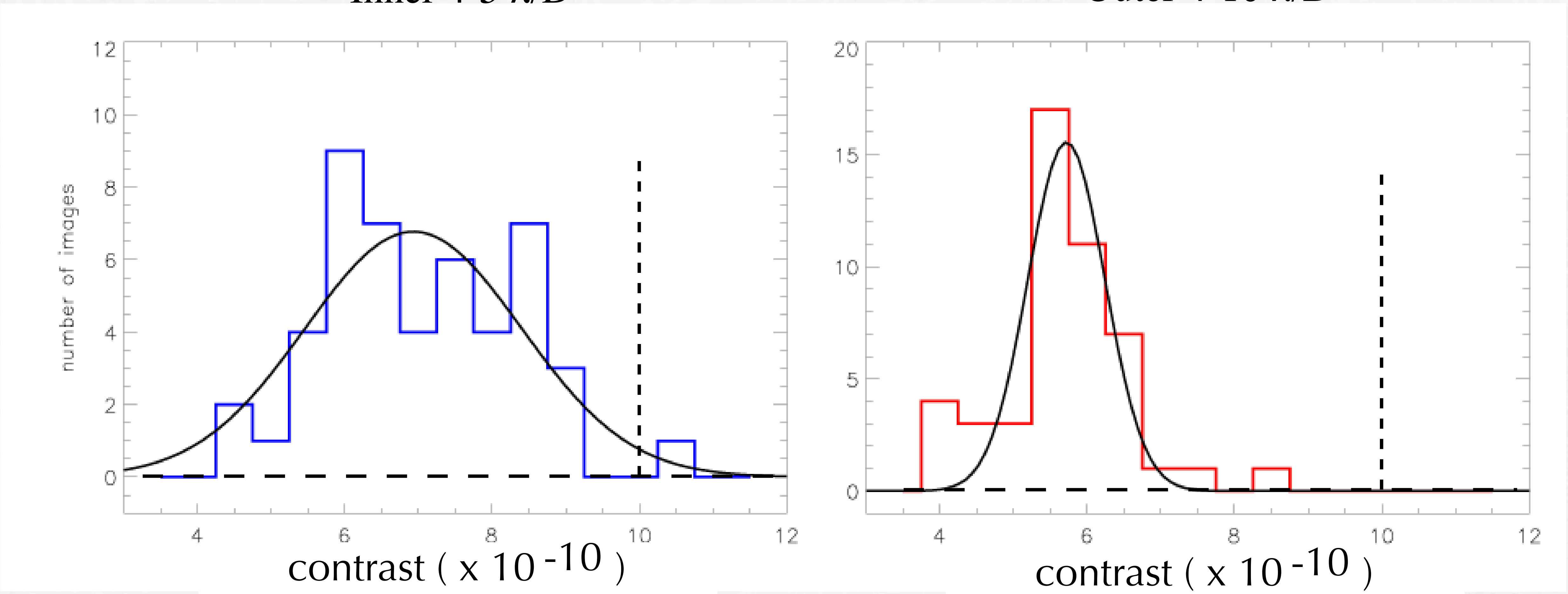




Contrast obtained in a sequence of images over a representative one-hour period in March 2006. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted "star". Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. One-σ error bars indicate the measurement noise estimated from pairwise data.

Repeatability of high contrast in a sequence of data sets

Inner 4-5 λ/D   Outer 4-10 λ/D



Summary of contrast measured during six different hour-long data sets (in March 2006) over the inner and outer high contrast fields (again in blue and red respectively), indicates the contrast repeatably exceeds billion-to-one.

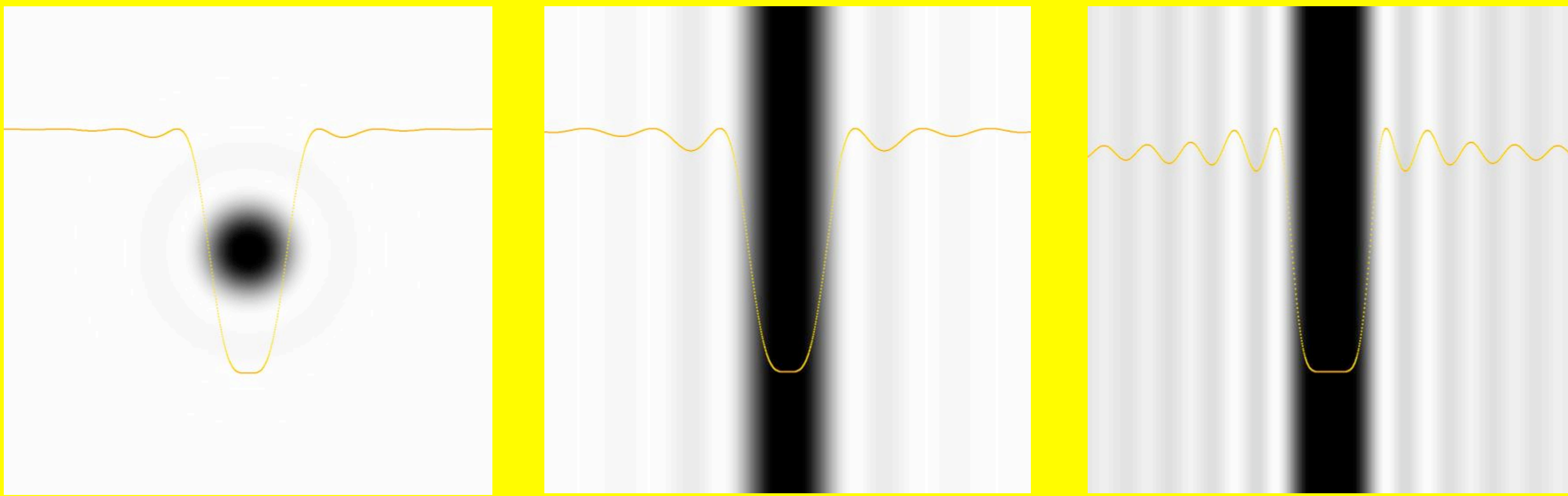
Recent HCIT Lyot coronagraph demonstrations

- Demonstrations of 6x10-10 contrast in narrowband light
  - Direct measurement of contrast in coronagraph images
  - Repeatable contrast (TPF-C Milestone #1 demonstration)
  - Stable contrast (open loop demonstration for 5 hours)
- Speckle nulling algorithm at science focal plane used for wavefront sensing and control
- Close agreement with Fresnel propagation models and speckle nulling models
- End-to-end demonstration, minimizes assumptions on the performance of missing components

Other experiments ongoing on the HCIT

- Extensions to the baseline speckle nulling algorithm (Burrows, Krist, Trauger)
- Binary realizations of 4th and 8th order occulting masks (Hoppe, Balasubramanian)
- Shaped pupil coronagraphs (Belikov, Kasdin, Vanderbei / Princeton)
- Alternate speckle nulling algorithms (Burrows, Borde, Traub, Kern)
- Spectral discrimination imaging (Biller, Close / U. of Arizona)

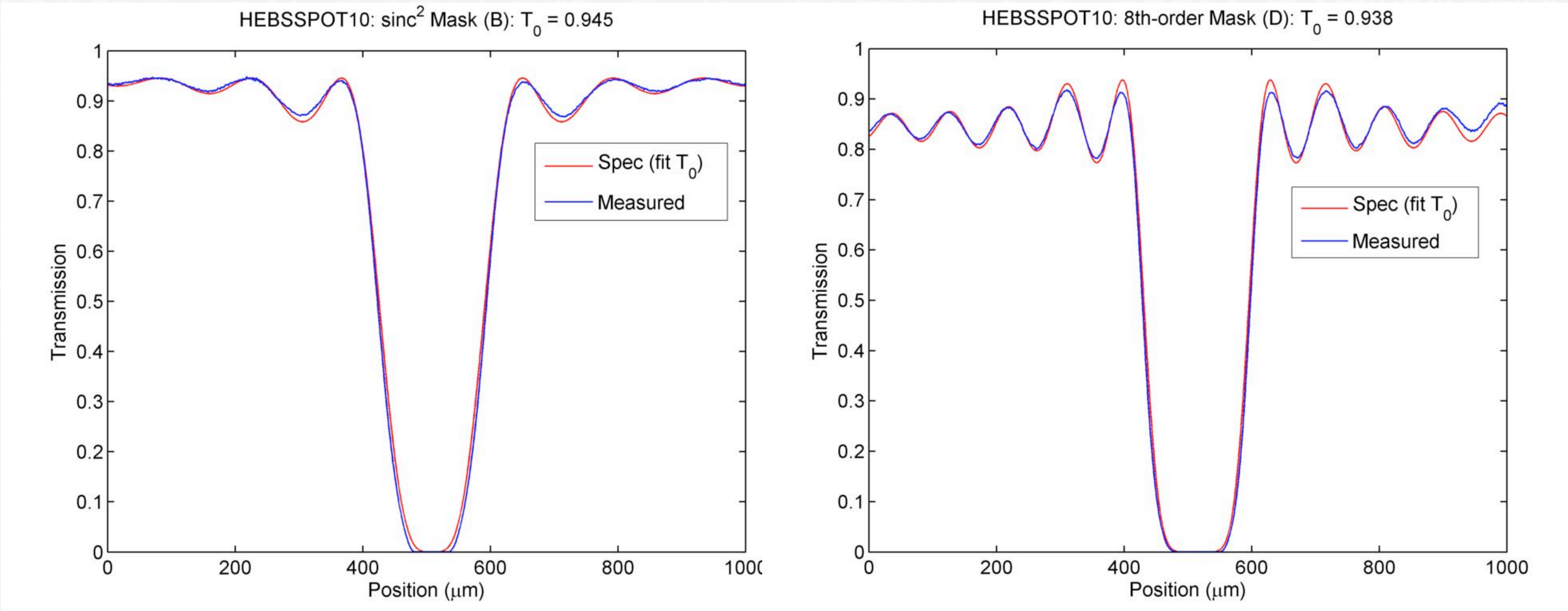
Selectable focal plane occulting masks



$$T(r) = \left[1 - \left(\frac{2J_1(\pi r)}{\pi r}\right)^2\right]^2 \qquad T(x) = \left[1 - \left(\frac{\sin(\pi x)}{\pi x}\right)^2\right]^2 \qquad T(x) = \left[\frac{2}{3} - \left(\frac{\sin(\pi x)}{\pi x}\right)^3 + \frac{1}{3}\left(\frac{\sin(3\pi x)}{3\pi x}\right)\right]^2$$

Transmittance profiles for three occulting spot apodizations. From left to right: a band-limited Bessel profile, a linear sinc^2 (4th-order) profile (Kuchner and Traub 2002), and a linear 8th-order profile (Kuchner, Crepp, and Ge 2004). The linear sinc^2 and 8th-order masks have been fabricated both in HEBS glass (Canyon Materials Inc.) and as binary masks on glass at JPL's MDL. New HEBS material is under development for broad (500-850 nm) spectral coverage and reduced phase shifts.

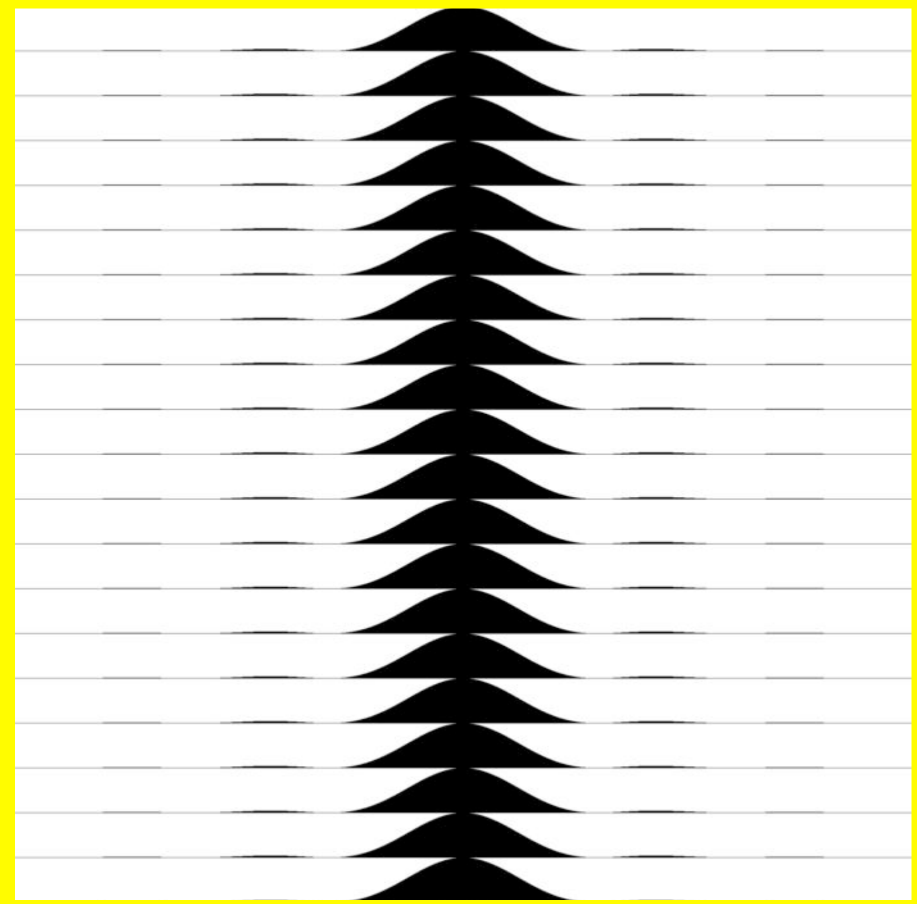
Measured occulter profiles



Linear 4th-order (left) and 8th-order (right) masks written in HEBS glass (Canyon Materials) at JPL's Microdevices Laboratory. Transmittance profiles have been measured under a microscope and compared with their respective analytic prescriptions.

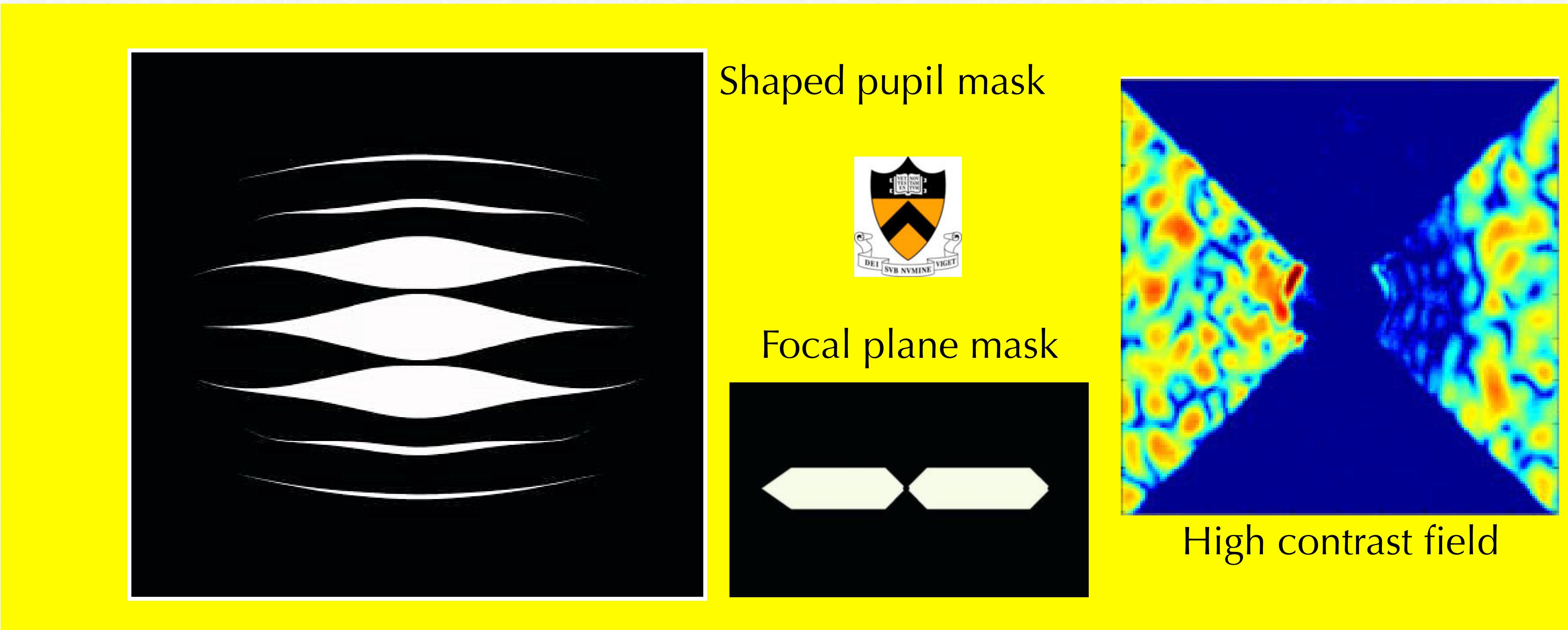
Lyot occulters in binary metallic form have been tested in HCIT

$$h(x) = P_y \left[1 - \sqrt{T_0} \left(1 - \left(\frac{\sin(\pi x/w)}{(\pi x/w)} \right)^2 \right) \right]$$



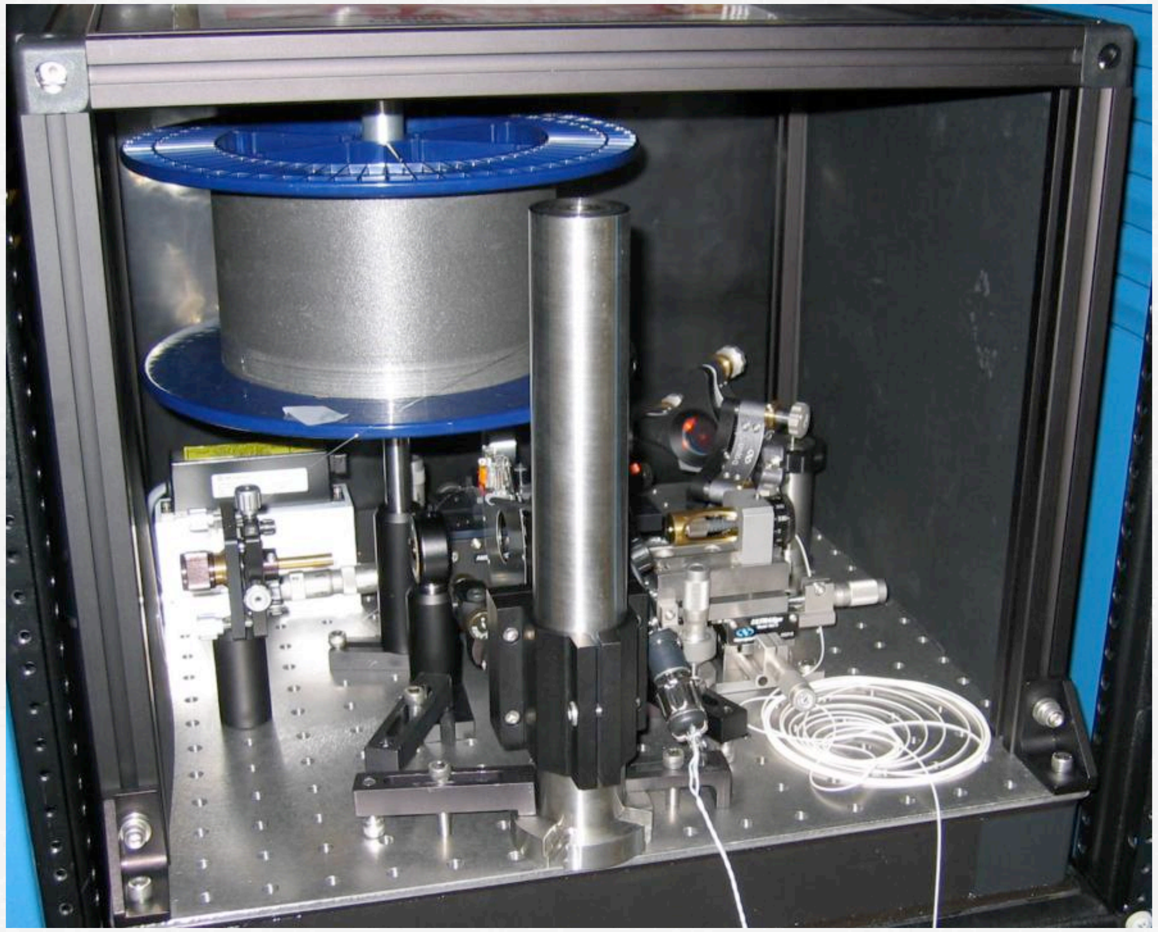
Transmittance profile for one of several binary occulting spot apodizations (black indicates opaque, white indicates clear) demonstrated in the HCIT. This is a band-limited linear sinc^2 (4th-order) profile (Kuchner and Traub 2002). A linear 8th-order profile (Kuchner, Crepp, and Ge 2004) has also been fabricated in binary form at JPL.

Shaped pupil coronagraph approach for high contrast imaging



At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque, white indicates clear) currently mounted and selectable in the HCIT. At right, the corresponding "bowtie" image plane mask. This "Ripple 3" design (Belikov et al, SPIE 6265-42) illustrates one example of alternative coronagraph schemes under investigation with the HCIT.

White light experiments use a supercontinuum white light source



HCIT laser pumped supercontinuum source is used for broadband (white) light.

Intensity is uniform within 10% over the a 600-900 nm spectral range.

Filter complement includes 2%, 10%, and 20% optical filter bandpasses centered on and around 633 nm and 800 nm.

Intensity is at least 50 times greater, and spectrum is flatter, than Xenon lamp used in previous HCIT white light experiments.

This greater intensity improves S/N in high-contrast white-light coronagraph images.

Summary: HCIT Lyot coronagraph demonstrations

- Achieved 6x10-10 contrast repeatably in narrowband light:
    - Direct measurement of contrast in coronagraph images
    - Repeatable contrast (as specified for the TPF-C Milestone #1 demonstration)
    - Stable contrast (contrast of 6x10-10 demonstrated *open loop* for 5 hours or more)
    - Speckle nulling algorithm used for wavefront sensing and control
    - Close agreement with Fresnel propagation and speckle nulling models
    - End-to-end demonstration, no assumptions on performance of missing components
- White light demonstrations are in progress, most notably:
    - Contrast of 3x10-9 demonstrated in 10% bandpass with HEBS occulters
    - Broad-band occulters leveraging spectral characteristics of HEBS glass
    - Extension to 10-20% bandpass white light
- Nulling algorithm refinements for precision wavefront correction are ongoing.

End